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USING PULSARS TO DETECT MASSIVE BLACK HOLE BINARIES VIA GRAVITATIONAL RADIATION: SAGITTARIUS A* AND NEARBY GALAXIES

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ABSTRACT

Pulsar timing measurements can be used to detect gravitational radiation from massive black hole binaries. The ∼106d quasi-periodic flux variations in Sagittarius A* (Sgr A*) at radio wavelengths reported by Zhao, Bower, & Goss (2001) may be due to binarity of the massive black hole that is presumed to be responsible for the radio emission. A 106d equal-mass binary black hole is unlikely based on its short inspiral lifetime and other arguments. Nevertheless the reported quasi-periodicity has led us to consider whether the long-wavelength gravitational waves from a conjectured binary might be detected in present or future precision timing of millisecond pulsars. While present timing cannot reach the level expected for an equal-mass binary, we estimate that future efforts could. This inquiry has led us to further consider the detection of binarity in the massive black holes now being found in nearby galaxies. For orbital periods of ∼2000d where the pulsar timing measurements are most precise, we place upper limits on the mass ratio of binaries as small as 0.06.

1. INTRODUCTION

Sazhin (1978) and Detweiler (1979) discussed the influence of long-wavelength (nanoHertz) gravitational radiation on the propagation of pulsar signals. Detweiler (1979) suggested a possible source of such radiation: binary massive black holes (MBHs) in distant galaxies. We have been engaged in a program to detect the stochastic background from the Universe of coalescing MBHs as well as to make estimates of the expected level. Here we consider the detection of gravitational radiation from the nearest objects.

We begin this inquiry by considering our Galactic Center (GC). There has been mounting evidence that the dark mass detected via proper motions of IR stars in the vicinity of Sagittarius A* (SgrA*) is a MBH (Eckart & Genzel 1997; Ghez et al. 1998; Maoz 1998; Ghez et al. 2000). Proper motion and absolute astrometry techniques lead to the identification of the compact non-thermal radio source Sgr A* with the MBH (Backer & Sramek 1999; Reid et al. 1999; Menten et al. 1997). The electromagnetic emission of Sgr A* may be either from the faint glow of matter being accreted on the MBH or from cooling in a small disk/jet system (see e.g. Narayan, Igumenshchev & Abramowicz 2000; Falcke 1996). At mm and short cm wavelengths where the effects of interstellar scattering are minimized the intrinsic source has been determined to be of order a few AU, less than 100 Schwarzschild radii of the MBH (Lo et al. 1998; Doeleman et al. 2001).

Recently, Zhao et al. (2000) reported quasi-periodic flux variations of Sgr A* with a 106d period using observations at 1.3 and 2.0 cm from the VLA. The authors explored various models to account for the variation including the possibility that the periodicity is related to the orbit of a binary companion. The authors discount the binary scenario because the two holes would be easily resolved by high angular resolution VLBI imaging assuming that both were luminous. VLBI observations of Sgr A* at 22-43 GHz reveal only a single source (e.g., Bower & Backer 1998; Lo et al. 1998; Doeleman et al. 2001). One could further argue that owing to the short lifetime for coalescence of an equal-mass binary MBH in Sgr A* the system is unlikely. The residuals in proper motion measurements of Sgr A* can also be used to place an orientation dependent limit on the mass of a dark companion to the Sgr A* MBH. While binarity of the Sgr A* MBH is an unlikely explanation for the flux variations reported by Zhao *et al.*, we proceed in this paper to explore the detectability of the gravitational radiation from such a binary in millisecond pulsar (MSP) timing residuals.

The ratio of the hole masses now being measured in nearby galaxies (Magorrian et al. 1998; Merritt & Ferrarese 2001) to their distance is such that these objects are also candidate sources for detectable gravitational radiation if we make the binary hypothesis for them also. In this case we have no candidate period and are free to explore the limits on binary mass ratio at orbital periods where we are most sensitive, 2000 days.

In this article we first discuss in §2 the possible amplitude of perturbation of pulsar timing residuals by the conjectured Sgr A* binary MBH, including a discussion of possible mass ratios. In §3 we present our recent observations of MSPs and available archival data. This is followed by a periodogram analysis that yields the best limit we can reach with current data sets. §5 discusses the possibility of detecting binary MBHs in nearby galaxies for which hole masses have been estimated. In our final section we summarize our conclusions.

2. PERTURBATION OF PULSAR TIMING BY GRAVITATIONAL RADIATION FROM SGR A*

We use the superb formulation of the gravitational radiation from binary masses by Peters & Matthews (1963, hereafter PM63) to make detailed estimates of the amplitude $h(\vec{r}, t)$ of the possible gravitational emission from Sgr A*. We then follow the development by Sazhin (1978) and Detweiler (1979) of the influence of this radiation on the

electromagnetic pulses emitted from a pulsar as it travels through space-time that is perturbed by $h(\vec{r},t)$. In short, pulse propagation through complete cycles of $h(\vec{r},t)$ have no net effect on the arrival time. There is only a perturbation of the arrival time by the incomplete cycles traversed at the pulsar and at Earth.

We use Eqn. 16 in PM63 to calculate the luminosity L_{GW} of the gravitational wave (GW) from the assumed circular binary system in the GC

$$L_{\rm GW} = \frac{32}{5}\frac{m^5 q^2}{a^5(1+q)^4}\frac{G^4}{c^5} = 2.9\times 10^{43}\ {\rm erg\ s^{-1}}\frac{q^2}{(1+q)^4} \quad (1)$$

where $m = 2.6\times 10^6\ M_\odot$ is the total mass of the system(Ghez et al. 2000), q is the mass ratio ($q \le 1$), and a is the semi-major axis. The numerical result uses Kepler's Law $a^3 = GmP_{orb}^2/4\pi^2$ and the 106d orbital period of interest. For $P_{orb} = 106d$, $a = 59$ AU. Here and below we assume a circular orbit which is likely following the combined actions of dynamical friction and radiation.

From the energy density of a GW, which is $U = c^2\dot{h}^2/32\pi G$ (Eqn. 2 in PM63), we derive the dimensionless amplitude of the GW;

$$h = 34\left(\frac{m^{1.67}G^{1.67}}{P_{orb}^{0.67}d}\right)\frac{q}{(1+q)^2} = 6.3\times 10^{-14}\frac{q}{(1+q)^2}, \quad (2)$$

where d is the distance to the emitter, 8 kpc. In this expression h is averaged over all orientations of the observer relative to the plane of the binary orbit. Since we obtained this expression from the total energy density, which is the sum of the contributions from two polarizations, h_+ and $h_\times$, h is actually the quadrature sum of these two polarizations. In order to find the dependence on inclination angle, i, we use the expression for the average power radiated per solid angle in PM63. This shows that the power radiated along the axis of the orbit is 8 times that for an edge-on view.

As discussed by Detweiler (1979) and others the dimensionless strain h produces an apparent redshift in the pulsar frequency. A periodic source of GW then will produce a periodic shift in pulse arrival time from propagation through the gravitational radiation with an amplitude, δt, which is given by

$$\delta t \sim \frac{hP_{\rm GW}}{2\pi} = 22\ {\rm ns}\sqrt{(1+6\cos^2 i+\cos^4 i)}\frac{q}{(1+q)^2}, \quad (3)$$

where $P_{\rm GW}$ represents the period of the gravitational wave, $P_{orb}/2$. The mass ratio factor is at most 1/4. The angular factor ranges from 1 to 2.8. Therefore, δt is less than 16 ns, and its average value over all solid angles is

$$\delta t \le 46\ {\rm ns}\frac{q}{(1+q)^2}, \quad (4)$$

which is 11 ns for $q = 1$ and less for any other mass ratio.

Detweiler (1979) discusses the dependence of the GW signature in pulsar timing on the angle between the GW and the pulsar sightline. Pulse propagation times are perturbed by the GW owing to incomplete traversal of a cycle of the GW both at the pulsar as pulses are emitted and at the Earth upon pulse reception. In the plane wave approximation the resulting timing residual, δt, is

$$< \frac{\delta t}{P_{\rm GW}} >= \frac{1}{2\pi}\left[\frac{(1+\gamma)}{2}h\right](f(ct_{\rm r}) - f(ct_{\rm e}+\gamma l)). \quad (5)$$

where γ is the cosine of the angle, ϕ, between the GC and the pulsar, where $\phi = 0$ is defined as the pulsar lying along the line of sight to the GC. $f(t)$ is the dimensionless phase term that comes from the fragments of the GW traversed at the emitter (e) and receiver (r) ends ($f \le 1$). The times of emission and reception are $t_{\rm e}$ and $t_{\rm r} = t_{\rm e} + l/c$, respectively, and the factor γl is the projection of the pulsar distance l along the GW propagation vector. Note that when $\gamma = +1$, there is no effect from the GW: a pulsar lying along the line of sight to the GC will experience no effect. The residual is also identically zero for $\gamma = -1$ which describes electromagnetic waves (EMW) traveling in the opposite direction as the GW. The residual increases as the EMW and GW become perpendicular, and reaches a maximum just before they become parallel. The angle between PSR B1937+21 and Sgr A* from Earth is 58° , and between PSR J1713+0747 and Sgr A* is 37° . The signal from the two pulsars will therefore be diminished from our earlier estimate in Equation 4 by a factor $(1+\gamma)/2 = 0.76$ and 0.90, respectively. This factor adjusts our earlier estimate of the maximum possible effect from 16 ns to 14 ns, and our estimate of the average effect from 11 ns to 10 ns due to an equal-mass binary.

If either of the sources were much closer to the GC than the Earth, then h in Eqn. 5 would need to be corrected for both the different wave amplitudes and the different angular factors. In our case all relevant distances (Earth to GC, J1713+0747 to GC, B1937+21 to GC) are 7-8 kpc, and are not known to better than 25% (Kaspi, Taylor, & Ryba 1994; Camilo, Thorsett, & Kulkarni 1994). Since the distances and therefore the phase factors are unknown, and the amplitudes of the two effects at the two ends are roughly equal, it is even possible that the two phase factors will be nearly the same, vastly diminishing the signal. The signal at emitter site will represent GW level 10^4 years ago, probably not too different from today. The phase factor from the receiver end will produce a signature that is correlated with other pulsars, whereas the emission terms will be uncorrelated. Clearly observations with an array of pulsars at different angles and distances are critical to overcoming this "emission phase" noise.

We have used a mass ratio of $q = 1$ to calculate the maximum signal we might expect. There are two arguments against a large mass ratio. One is based on evolutionary arguments and the other on proper motion observations of Sgr A*. First, the lifetime for gravitational inspiral from a 106d orbit for $q = 1$ is 3×10^6 y; the lifetime increases with $(1+q)^2/q,\ q \le 1$. After two galaxies merge the timescale for their central black holes to reach such an orbit is unknown, and could be from 30 million years to a Hubble time (e.g., Rajagopal & Romani 1995, Gould & Rix 2000). Toth & Ostriker (1992) rule out the possibility of a recent merger using models of disk heating via accretion of satellite galaxies. They demonstrate that no more than 4% of the mass of the galaxy could have been accreted within the last 5 billion years. Xu & Ostriker (1994) model the accumulation of a central MBH in a scenario with much less disk heating: the accretion of primordial $\sim 10^6$ M$_\odot$ black holes. They show that a quickly accumulating MBH in the GC is actually not what we should expect; dynamical friction and gravitational radiation serve to eject massive

objects from the center as well as accreting them. Galaxies such as ours, they conclude, are usually host to zero, one or two MBHs. In any case, a crude estimate of the likelihood that we happen to be living in the epoch of coalescence of a $2.5 \times 10^6 M_\odot$ 106d binary is $\sim 3 \times 10^6$y/(age of Milky Way) or less than 0.1%; in other words it is unlikely that we are observing the pair of black holes at the moment of their coalescence.

The second argument uses the VLA and VLBA measurements of the proper motion of Sgr A* (Backer & Sramek 1999; Reid et al. 1999) to place a limit on the mass ratio. The three reported VLBA measurements span almost exactly 7 cycles of the observed 106d quasi-periodicity. The middle point is offset in phase from the end points by 0.5. The scatter about the line connecting the VLBA measurements, about 0.5 mas, provides an estimate of the maximum separation between the observed mass and the center of mass of the system along the axis where the observational data are most sensitive. If we assume Sgr A* is centered on the larger of the two masses, this places a limit on the mass ratio of $q <$ (0.5 mas)(8 kpc)/59 AU = 0.07. This limit is mainly in the EW direction where the VLBA data are most precise. Thus, the limit is strictly on $q \sin(\theta)$ where θ is the inclination of the orbital plane to the plane defined by the NS direction and the line of sight. Interestingly, the VLBA data nearly rule out the possibility that we are seeing the less massive member of the conjectured binary.

In conclusion, we estimate that the perturbation in pulsar timing residuals is no larger than $\sim$ 14 ns for the pulsars we consider here. In the following section, we present the current level of precision in our measurements, and discuss the feasibility of detecting a 14-ns sinusoidal amplitude in our timing residuals.

3. OBSERVATIONS

We have been conducting monthly observations at 0.43 GHz, 1.4 GHz and 2.4 GHz of an array of MSPs using the Arecibo Observatory 300 m telescope[1] since December 1997. These data are used to make precision arrival time measurements for a variety of astrophysical goals. We used the Arecibo-Berkeley Pulsar Processor (ABPP), which is a multi-channel, coherent dispersion removal processor[2] with 112-MHz total bandwidth capability.

In this paper we include only PSRs J1713+0747, B1855+09 and B1937+21 because their data sets span the longest time, 3.2 years, and they have the best timing precision. For PSRs J1713+0747 and B1855+09 we use 56-MHz bandwidth for observations at 1.4 GHz, and 112-MHz for 2.4 GHz, while for PSR B1937+21 we use 45-MHz overall bandwidth at 1.4 GHz and 55-MHz at 2.4 GHz. Calibrated total intensity profiles were formed from signals with orthogonal circular polarization. The profiles were then cross correlated with a template to measure times of arrival (TOAs) relative to the observatory atomic clock. Small errors in the observatory UTC clock, of order 1 μs, were corrected based on comparison of local time to transmissions from the Global Positioning System of satellites (GPS) using the Totally Accurate Clock receiver at the observatory. GPS time is then corrected to the TAI scale via publications from the Bureau International des Poids et Mesures (BIPM). The resulting TOAs are modeled for spin, astrometric, and, when relevant, binary parameters using the TEMPO software package[3]. In this paper we use the residuals from the model to look for other effects.

After fitting for phase, spin period (P), period derivative ($\dot{P}$), right ascension, declination, and proper motion in the B1937+21 data, and additionally for the 5 Keplerian binary parameters in PSR J1713+0747 and PSR 1855+09, we have the residuals shown in Figure 1. Note that we did not fit for the Shapiro delay which has been measured in both PSRs J1713+0747 and B1855+09, but rather set the values to the best-fit values published (Kaspi, Taylor, & Ryba 1994; Camilo, Foster, & Wolszczan 1994). The weighted RMS of the day-averaged residuals are 0.35 μs, 0.53 μs, and 0.14 μs for J1713+0747, B1855+09, and B1937+21, respectively.

In our periodogram analysis (§4) we also use the Princeton Mark II and Mark III data published and made public by Kaspi, Taylor, & Ryba (1994, hereafter KTR94) . This was a biweekly monitoring program that spanned 8 years. KTR94 carefully removed dispersive effects from each of their TOAs on PSR B1937+21, which we have not done in the ABPP data. Due to our large bandwidth (45 MHz vs their 10 MHz) we achieve a similar level of precision with shorter data span.

PSR B1937+21 has been demonstrated by KTR94 to be unstable on time scales of about 5 years, but on the time scales over which we are interested here, 25-100 d, any instability it may have is below the noise level of our data, about 0.14 μs.

The timing measurements at Arecibo Observatory have a short-term precision of order 50 ns on the "best" millisecond pulsars with integrations of 3 minutes over a single hour. This suggests that with sufficient averaging and frequent observation we could detect the 14-ns amplitude perturbation discussed above. However, we have not achieved this level of precision over the full data span of our current data ($\sim$ 3 y). We suspect that the discrepancy is the result of distortion of the average pulse profile by diffractive scintillation across our wide band (50-110 MHz). The pulse profile evolves with frequency over the band, and diffractive scintillation weights different parts of the band more heavily on different days. We are working on an algorithm to suppress this effect (Lommen & Backer 2001).

Nevertheless we proceed in §4 with a careful analysis of the current limits our data can place on the existence of a GC binary MBH.

4. PERIODOGRAM ANALYSIS

The residual data shown in Figure 1 represent an irregularly spaced, sparsely sampled system in which we look for periodicities. As such, the method described by Cumming et al. 1999 (hereafter C99) for constructing and normalizing periodograms is ideal. C99 were searching for planets in spectroscopic velocity data from the Lick Observatory.

[1] The National Astronomy and Ionosphere Center Arecibo Observatory is operated by Cornell University under contract with the National Science Foundation.

[2] 'coherent' means that the dispersion is removed in the voltage domain prior to power detection.

[3] http://pulsar.princeton.edu/tempo

The astronomical goal is very different, but the method is essentially identical. This periodogram approach is similar to the approach taken by Bailes, Lyne, & Shemar (1993) to look for planets around slow period pulsars.

We constructed periodograms for the residual timing data in the following way. We fit the data to the function $A\cos\omega t + B\sin\omega t + C$ by minimizing χ^2, at a range of frequencies, $\omega = 2\pi f$, centered at the nominal GW frequency, f_0 of 1/53 d^{-1}. The arbitrary offset 'C' is critical for sparsely sampled data as demonstrated by C99, even though the mean of the residuals is fit by the period polynomial. The range of frequencies we considered was dictated by the width of the periodogram feature detected by Zhao, Bower, & Goss (2001) which was approximately unity for the 2-cm data. We chose to look at a frequency range, $\Delta f = \frac{1}{2}f_0$, which is 0.014 to 0.024 d^{-1} corresponding to a range of periods from 42 to 71 days. The frequency range considered in the analysis is very important as the smaller the range considered for detection, the more sensitive the measurement will be. In order to sample the possible periodicities completely, the approximate size of the steps by which we needed to sample this frequency range is $\frac{1}{S}$, where S is the time span of the data set. Since we are using data sets of different spans (namely the Kaspi data which is 8 years long, and the post-upgrade data which is 3 years long) we chose a frequency spacing that would slightly oversample the Kaspi data, and 4 times oversample the post-upgrade data: stepsize $= 2\times10^{-4}$ d^{-1}.

In Figure 2 we use the following formalism, taken from C99, to plot the periodogram power $z(\omega)$ as a function of ω.

$$z(\omega) = \frac{(N-m-3)}{2}\frac{(\chi^2 - \chi^2(\omega))}{\chi^2(\omega_0)} \tag{6}$$

where N is the number of degrees of freedom of the data, m is the number of independent fit parameters, χ^2 is the weighted sum of the squares of the original residuals, $\chi^2(\omega)$ is the weighted sum of the squares of residuals after the periodicity fit is included and ω_0 is the frequency that gives the lowest $\chi^2(\omega)$. $N-m-3$ is the number of degrees of freedom of the periodicity fit and corresponds to a residual fit using the m parameters in the pulsar model, and 3 additional parameters corresponding to fitting A, B, and C. Therefore $z(\omega)$ is the amount by which the χ^2 is reduced by adding the periodic signal to the data, normalized by the best fit χ^2. Note that $z(\omega)$ is normalized such that $z(\omega) = 1$ for no sinusoidal signal present in the residuals.

We decided not to include the data from PSR B1855+09 in our analysis due to the higher RMS of its residuals compared to the other pulsars. The normalization of the statistic $z(\omega)$ allows us to average the three periodograms from the 3 remaining data sets to acquire the final periodogram shown in Figure 2. We also repeated the analysis using only PSR B1937+21 data and achieved very similar results.

Is there any significant detection of gravitational radiation in the periodogram shown in Figure 2? To answer this question we use Monte Carlo simulations to determine whether the peak at 60.5 d, with a value of 2.5, is a spurious effect of the noise. Following the method described in C99, we created 400 sets of simulated residuals, with no periodic signal, but with identical statistics to the real data. We asked what percentage of these 400 realizations would conspire to produce a peak between 42 and 71 days, as high or higher than 2.5. This percentage is called the "false-alarm probability", and if it is higher than some threshold the detection is spurious. The threshold must be determined by the specifics of the problem, and can be anywhere from 10^{-5} to 0.1. C99, for example, used a threshold of 10^{-5} because there were systematics in their data that would imitate a signal at higher values. Creating identical statistics to the original data set proved to be challenging and also crucial to producing a meaningful false-alarm probability. In all cases we replicated the sampling of the original data. When we merely generated random numbers with a gaussian noise distribution and the same RMS as the original data, the false-alarm probability was 100%. This is due to the "redness" of the variation in the residuals, i.e., neighboring residuals have much smaller RMS with respect to each other than the overall RMS of the data set. Therefore by creating gaussian noise with a particular RMS we were creating a data set with much higher RMS between neighboring points than was present in the original set. The redness of pulsar timing residuals is commonly called "timing noise" and has been studied and discussed by a number of authors, and will not be discussed here (Cordes & Helfand 1980; Arzoumanian et al. 1994; Kaspi, Taylor, & Ryba 1994). To account for this low-frequency variation we fit for 3 additional period derivatives in each data set. This is identical to removing a 5th order polynomial from each data set. We are confident that this additional fitting would not remove any signal at a 53 day period since a 5th order polynomial has 5 zero-crossings, and our data sets are all at least 3 years long. We may, therefore, be removing variations as short as (3 yr/5) $\sim$ 200 days but no shorter. Additionally, to fabricate the data we merely randomly reordered the real data, i.e. randomly assigned real residuals to the wrong dates, to assure that the statistics were identical. The final false alarm probability for producing the peak shown in Figure 2 was 23%, and thus the detection is spurious. To be sure we are not washing out features in the power-spectrum present in any one data set we have performed this analysis on each data set individually and obtained very similar results.

In order to find the minimum amplitude detectable in our data we used Monte Carlo simulation in the following fashion. We simulated timing residuals with the same statistical properties as our real data using the same method described above, and injected a signal at a 53-day period at a variety of amplitudes. The amplitude that we designate as our 'limit' corresponds to the amplitude where 99% of the random realizations of simulated data produced a power amplitude larger than that which we actually measure. This amplitude, $R = 0.15$ μs, represents the minimum amplitude we can detect with our current data.

5. NEARBY MASSIVE DARK OBJECTS

What is the probability that massive dark objects (MDO) in other galaxies are effecting our timing residuals? Magorrian et al. (1998) determined the masses or mass limits of 29 MDOs in nearby galaxies using HST photometry and ground-based spectroscopy of the galaxies. Several independent studies have demonstrated that these estimates are systematically high(van der Marel 1999; Wandel

1999; Ferrarese & Merritt 2000). van der Marel (1999) suggests the discrepancy is due to the assumption of velocity isotropy made by Magorrian et al. Merritt & Ferrarese (2001) improved the mass determination by using the extremely tight relationship between MDO and the velocity dispersion of the host bulge. In our analysis we use the Magorrian et al. sample of galaxies with the updated masses by Merritt & Ferrarese (2001).

We choose an advantageous orbital period for this discussion, 2000 days, where our data place the most stringent limit, and the lifetimes of the orbital systems are longer. The wavelength of the GW emitted from a 2000-day system is 1000 days, which is the length of our data set, so we must be careful that our pulsar model fitting would not remove the signal we wish to detect. A third period derivative fit or higher order would do so. Consequently, in order to obtain a meaningful limit we did not fit for the additional 3 derivatives of the period as we did for the previously described periodogram analysis, but rather used the residuals shown in Figure 1 which include only a single period derivative. By the same technique described in §4 we determined that the detectable amplitude at this period is 170 ns. In Table 2 we show the amplitude of the effect on the timing residual from each of the objects studied by Merritt & Ferrarese (2001) assuming the MDOs are equal-mass binaries with 2000-day orbits. Only those which produce a residual amplitude greater than 10 ns are tabulated. The amplitude shown is averaged over all solid angles. The amplitudes are as large as 850 ns which would be detectable in our data. However, the probability of detecting such an object during coalescence is proportional to its lifetime. Lifetime, τ, scales with q, M, and P_{orb} as follows.

$$\tau = 8.0 \times 10^4 \text{ y} \frac{(1+q)^2}{q} \left(\frac{m}{10^9 \mathrm{M}_\odot}\right)^{-5/3} \left(\frac{P_{orb}}{2000d}\right)^{8/3} \quad (7)$$

With these larger mass systems, we gain amplitude of the gravitational wave ($\propto m^{5/3}$), but lose reasonable lifetime of the system by the same factor. Fortunately, lifetime also scales strongly with orbital period in our favor ($\propto P_{orb}^{8/3}$), so we have much to gain by looking at longer periods. We place upper limits on q for these objects in Table 2 just as we have for the GC using the 170-ns detectable amplitude. These limits are as small as $q \leq 0.06$, which correspondingly give much longer lifetimes for the systems as shown in the last column. Objects with a reasonable lifetime (~1 Gyr) have a P_{orb} too large to be detectable by the pulsar measurements.

6. CONCLUSION

Gravitational radiation of an equal-mass 2.5 $\times 10^6$ $\mathrm{M}_\odot$ black hole binary at the GC would produce a periodicity in pulsar arrival times of order 10 ns. While this is an order of magnitude below the limits of present data presented in this paper, in the future a special observing effort might reach such a detection level. However, published proper motion measurements of Sgr A* place a limit on the mass ratio of any such binary of 20:1 for low inclinations and EW orientation. In this case the gravitational radiation effects would be below detection limit in pulsar timing. A small mass ratio is also likely given consideration of the coalescence time scale and the absence of any evidence of a recent large mass accretion event in the GC.

The known MDOs in nearby galaxies, if binary MBHs with orbital periods around 2000d, would produce a larger signal, up to ~ 1 μs, than that estimated for Sgr A*. However the lifetimes to gravitational radiation inspiral for such binaries are shorter than the already short lifetime of Sgr A* and therefore lower the probability that we are seeing them in this phase of evolution. With a number of such objects in existence, the probability increases that at least one of them is still in a 'young' binary state, and might be seen in pulsar timing residuals. Maintaining of precision pulsar monitoring programs with long and continuous coverage is important for the future of such detection efforts. The "Pulsar Timing Array", our precision millisecond pulsar timing program, extends the work we have described here to include the entire ensemble of MBH-MBH systems in the universe. This ensemble produces a stochastic GW background at a level that we can detect. This measurement will place important constraints on the origin and evolution of MBHs.

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REFERENCES

Arzoumanian, Z., Nice, D. J., Taylor, J. H., & Thorsett, S. E. 1994, ApJ, 422, 671
Backer, D. C., & Sramek, R. A. 1999, ApJ, 524, 805
Bailes, M., Lyne, A. G., & Shemar, S. L. 1993, In ASP Conf. Ser. 36, Planets around Pulsars, ed. J. A. Phillips, S. E. Thorsett, & S. R. Kulkarni (San Francisco: ASP), p. 19
Bower, G. C., & Backer, D. C. 1998, ApJ, 496, L97
Camilo, F., Foster, R. S., & Wolszczan, A. 1994, ApJ, 437, L39
Camilo, F., Thorsett, S. E., & Kulkarni, S. R. 1994, ApJ, 421, L15
Cordes, J. M., & Helfand, D. J. 1980, ApJ, 239, 640
Cumming, A., Marcy, G. W., & Butler, R. P. 1999, ApJ, 526, 890
Detweiler, S. 1979, ApJ, 234, 1100
Doeleman, S. S., Shen, Z. ., Rogers, A. E. E., Bower, G. C., Wright, M. C. H., Zhao, J. H., Backer, D. C., Crowley, J. W., Freund, R. W., Ho, P. T. P., Lo, K. Y., & Woody, D. P. 2001, AJ, 121, 2610
Eckart, A., & Genzel, R. 1997, MNRAS, 284, 576
Falcke, H. 1996, In IAU Symp. 169: Unsolved Problems of the Milky Way, ed. L. Blitz, P. Teuben (Dordrecht: Kluwer), volume 169, p. 169
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Ghez, A. M., Klein, B. L., Morris, M., & Becklin, E. E. 1998, ApJ, 509, 678
Ghez, A. M., Morris, M., Becklin, E. E., Tanner, A., & Kremenek, T. 2000, Nature, 407, 349
Gould, A., & Rix, H. 2000, ApJ, 532, L29
Kaspi, V. M., Taylor, J. H., & Ryba, M. F. 1994, ApJ, 428, 713
Lo, K. Y., Shen, Z., Zhao, J., & Ho, P. T. P. 1998, ApJ, 508, L61
Lommen, A. N., & Backer, D. C. 2001, ApJ, in preparation
Magorrian, J., Tremaine, S., Richstone, D., Bender, R., Bower, G., Dressler, A., Faber, S. M., Gebhardt, K., Green, R., Grillmair, C., Kormendy, J., & Lauer, T. 1998, AJ, 115, 2285
Maoz, E. 1998, ApJ, 494, L181
Menten, K. M., Reid, M. J., Eckart, A., & Genzel, R. 1997, ApJ, 475, L111
Merritt, D., & Ferrarese, L. 2001, MNRAS, 320, L30
Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2000, ApJ, 539, 798
Peters, P. C., & Matthews, J. 1963, Phys. Rev., 131, 435
Rajagopal, M., & Romani, R. W. 1995, ApJ, 446, 543

Reid, M. J., Readhead, A. C. S., Vermeulen, R. C., & Treuhaft, R. N. 1999, ApJ, 524, 816
Sazhin, M. V. 1978, Soviet Astronomy, 22, 36
Thorsett, S. E., & Phillips, J. A. 1992, ApJ, 387, L69
Toth, G., & Ostriker, J. P. 1992, ApJ, 389, 5
van der Marel, R. P. 1999, In IAU Symp. 186: Galaxy Interactions at Low and High Redshift, ed. J. E. Barnes, and D. B. Sanders (Dordrech: Kluwer), volume 186, p. 333
Wandel, A. 1999, ApJ, 519, L39
Xu, G., & Ostriker, J. P. 1994, ApJ, 437, 184
Zhao, J., Bower, G. C., & Goss, W. M. 2001, ApJ, 547, L29

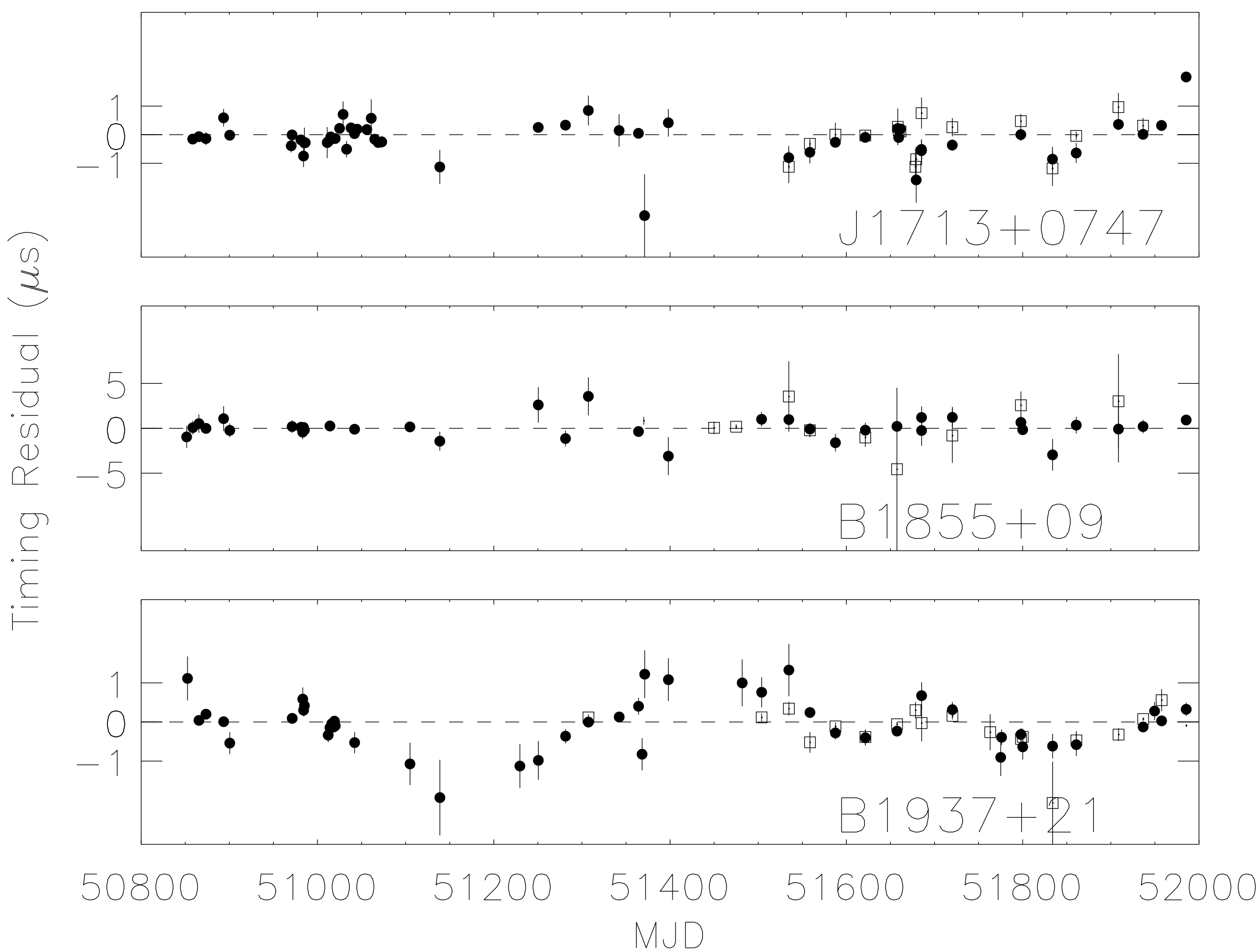

Fig. 1.— Timing residuals for PSRs J1713+0747, B1855+09 and B1937+21 using our data taken after the Arecibo upgrade. Filled circles are 1420-MHz data and squares are 2380-MHz data.

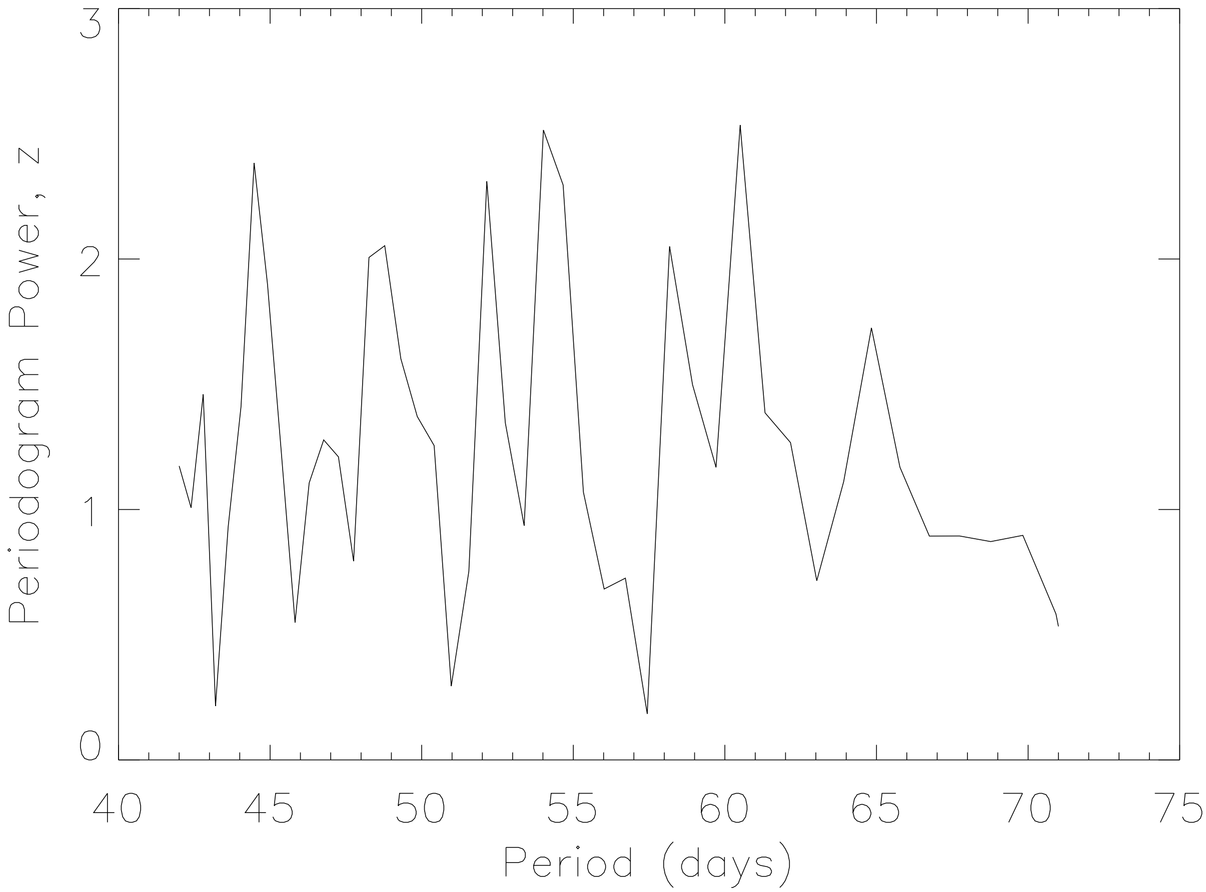

Fig. 2.— Periodogram power, z, vs. period in days as measured in residuals from PSRs B1937+21 and J1713+0747.

Table 2
Pulsar Timing Residuals of Binary Massive Black Holes

Object	Mass[a] $\left[\log \frac{m}{M_\odot}\right]$	Distance [Mpc]	Residual[b] [ns]	Lifetime [b] [y]	Limit to Mass Ratio, q	Lifetime[c] [y]
NGC1399	9.0	17.9	327	2.9E+05	0.18	5.7E+05
NGC1600	9.0	50.2	102	3.3E+05	⋯	⋯
NGC2300	8.7	31.8	57	9.3E+05	⋯	⋯
NGC2832	9.3	90.2	157	1.2E+05	0.66	1.3E+05
NGC3115	8.8	8.4	281	7.2E+05	0.22	1.2E+06
NGC3379	8.1	9.9	18	9.2E+06	⋯	⋯
NGC3608	8.2	20.3	10	7.6E+06	⋯	⋯
NGC4278	8.7	17.5	107	9.1E+05	⋯	⋯
NGC4291	8.7	28.6	63	9.3E+05	⋯	⋯
NGC4472	8.8	15.3	134	8.3E+05	⋯	⋯
NGC4486	9.2	15.3	845	1.3E+05	0.06	6.6E+05
NGC4552	8.7	15.3	119	9.3E+05	⋯	⋯
NGC4594	8.6	9.2	104	1.8E+06	⋯	⋯
NGC4621	8.3	15.3	26	4.2E+06	⋯	⋯
NGC4649	9.1	15.3	610	1.8E+05	0.08	6.6E+05
NGC4660	8.2	15.3	17	6.3E+06	⋯	⋯
NGC4889	9.4	93.3	256	7.1E+04	0.25	1.1E+05
NGC6166	9.0	112.5	50	3.0E+05	⋯	⋯

[a]From Merritt & Ferrarese (2001).

[b]Assumes equal-mass binary and orbital period of 2000 d.

[c]Assumes mass ratio shown in column 6 and orbital period of 2000 d.